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A HE II HEAT EXCHANGER TEST UNIT DESIGNED FOR THE LHC INTERACTION REGION MAGNETS

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ABSTRACT

The LHC interaction region (IR) inner triplets are cooled with stagnant pressurized He II at 1.9 K. All heat loads deposited in the pressurized He II bath will be carried away by saturated He II via a He II heat exchanger. The heat exchanger, made from a corrugated copper tube inside a stainless steel pipe, will be placed outside of and parallel to the cold mass in the cryostat. The current paper details the design work of a full scale He II heat exchanger test unit for the verification of LHC inner triplet magnet cooling system.

INTRODUCTION

The LHC interaction region (IR) inner triplet quadrupoles are cooled with stagnant pressurized He II at 1.9 K. A detailed description of the LHC inner triplet cryogenic system has been previously published[1-4]. As compared to the LHC arc magnet cryogenic system, the inner triplets are subject to larger dynamic loads at 1.9 K. This, in addition to system integration consideration, lead to the proposed placement of the He II heat exchanger to a position external to the cold mass. All heat loads absorbed in the pressurized He II bath at 1.9 K will be removed by the saturated He II flowing inside the heat exchanger pipe. The heat exchanger, made from a corrugated copper tube inside a stainless steel pipe, is about 30 m long and will be placed alongside the cold mass in the cryostat. The comparison between the heat exchanger arranged inside and outside of the cold mass has been made in a previous report[2] .The thermal design requirement for the external heat exchanger is to remove up to 180 W at 1.9K with a temperature drop limited to 50 mK.

A full-scale heat exchanger test unit has been designed at Fermilab and will be tested at CERN to provide experimental verification for the LHC inner triplet heat exchanger system design.

THERMAL DESIGN

This He II heat exchanger is a key component for the LHC inner triplet system. The heat exchanger test unit is designed for measurement of the temperature profile within the heat exchanger at different heat load. The experimental data from the heat exchanger test unit will serve to guide us in the heat exchanger design of the LHC inner triplet. The updated heat loads to the LHC inner triplet magnet system at various temperatures are listed in Table 1.

The temperature drop in each section can be estimated for a given heat load and channel dimensions. The total temperature drop consists of three parts: that in the pressurized He II from the dummy magnet pipe center to the heat exchanger, across the HeII heat exchanger wall to the saturated He II, and that caused by the vapor pressure drop over the length of inner triplets.

The one dimensional turbulent heat transport in a channel containing He II is expressed by the Gorter-Mellink equation

$$\frac{dT}{dx} = -f(T)q^3 \tag{1}$$

where q is the heat flux in W/cm^2 and the quantity 1/f(T) is the effective thermal conductivity of He II and can be considered as a constant, 1200 W^3/cm^5K, at 1.9K for the pressurized He II at atmospheric pressure. The temperature drop in pressurized He II from the magnet simulator pipe center to the heat exchanger, ΔT_1, is obtained by the following expression

$$\Delta T_1 = \frac{q^3 L}{1200} \tag{2}$$

where L is the heat transfer length in which a temperature difference is needed to carry the heat flux q. The total temperature drop can be calculated by applying (2) on each section along the heat transport length.

The total thermal resistance across the heat exchanger wall consists of three parts: Kapitza thermal resistance on each side of the wall and the thermal resistance across the heat exchanger pipe wall thickness. The total temperature drop is estimated by assuming a constant heat conductance between the pressurized He II and saturated He II.

$$\Delta T_2 = q\left(\frac{1}{h_{k1}} + \frac{1}{h_{k2}} + \frac{t}{k}\right) \tag{3}$$

where h_{k1} and h_{k2} are Kapitza thermal conductance on each side of the pipe between He II and a solid wall, and t and k are the wall thickness and thermal conductivity of the heat exchanger pipe, respectively.

Table 1. Inner triplet heat loads

Temperature levels	50 to 75 K	4.5 K	1.9 K
Static heat loads (W)	210	9	18.0
Dynamic heat loads nominal (W)	0	20	162
Total heat loads (W)	210	29	180

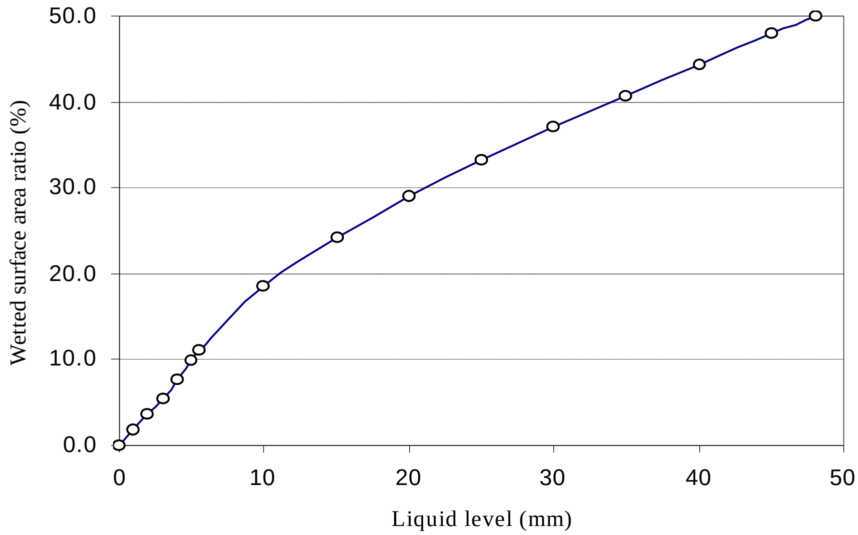

Figure 1. The wetted surface area of corrugated pipe as a function of liquid level

The temperature drop across the heat exchanger pipe wall can be obtained from (3). There are two unknowns in (3): one is the available heat transfer surface area from which the averaged heat flux q can be estimated and the other is Kapitza thermal conductance on both sides of the heat exchanger. The Kapitza conductance, h_k, can be estimated using the following suggested forms[5]

$$h_k = 0.9T^3 \text{ kW/m}^2\text{-K} \quad \text{for clean surface} \tag{4}$$

$$h_k = 0.4T^3 \text{ kW/m}^2\text{-K} \quad \text{for dirty surface} \tag{5}$$

The estimated Kapitza conductance on each side of the heat exchanger pipe is 2650 W/m^{2}K at an average temperature of 1.88 K for a fabricated surface with no special treatment of the surface.

The heat exchanger pipe inner surface is only wetted partially by the flowing saturated He II. The wetted surface area is a function of the liquid level inside the corrugated pipe. The percentage of the wetted surface area as a function of the liquid helium level is shown in Figure 1. The total inner surface area of the heat exchanger pipe, 30 m long, is about 12.54 m^2.

The pressure drop inside the corrugated pipe is calculated using the correlation given in the literature.[6] The temperature drop ΔT_3 is due to the vapor pressure drop in the 30 m long corrugated pipe. Table 2 summarizes each temperature drop along the heat transport path from magnet simulator pipe center to the exit of the corrugated pipe. The temperature drop across the wall is estimated at a heat load of 180 W. The wetted surface is assumed to be 30% of the inner surface area and the solid wall thermal resistance is negligible.

Table 2. Temperature drop calculation results

Location of temperature drop	Temperature drop (mK)
ΔT_1	11.2
ΔT_2 (wetted surface area is 30%)	36.1
ΔT_3	3.7
ΔT total	51.0

MASS FLOW AND YIELD

The mass flow rate required for the heat exchanger test unit depends on the heat load to the system, latent heat, and liquid yield after the JT valve

$$\dot{m} = \frac{Q}{y\,l} \tag{6}$$

where Q is the heat load to the system in W and λ is the latent heat of saturated He II in J/g. The yield y can be obtained by equating the enthalpies before and after expansion[5]

$$y = \frac{h_v - h_1}{h_v - h_l} \tag{7}$$

where h_1 is the enthalpy before expansion, h_v and h_l are enthalpies of saturated vapor and liquid respectively. For the helium at 1.2 bar and 2.6 K before the JT valve, the yield will be 82% after expansion. The required mass flow is 10 g/s for a heat load of 180 W and 15 g/s for a heat load 270 W.

HEAT EXCHANGER TEST UNIT

The heat exchanger test unit consists of a feedbox, four identical modules and one turnaround end. The four identical modules are connected in series and one end is interfaced with the turnaround end and the other is connected to the feedbox. Each one of the modules is 7.5 meters long and 508 mm in diameter. A simplified flow schematic for the He II heat exchanger test unit is shown in Figure 2. The saturated 1.8 K helium vapor is pumped through a JT heat exchanger to cool the incoming helium supply for the corrugated tube heat exchanger in the cryostats to around 2.6 K. A phase separator is connected to the helium supply of the test stand and helium will be separated into liquid and vapor phases. The liquid helium is used to cool the heat exchanger test unit down to liquid helium temperature via a control valve. The JT valve is opened to cool the system down to 1.8 K once the system is filled with liquid helium. The temperature drops to 1.8 K past the JT valve and vaporized helium is pumped by a cold compressor. The thermal shield is cooled by cold helium vapor from the phase separator to intercept the static heat load from room temperature. A stainless steel pipe of 143 mm in diameter, serving as a dummy magnet, is equipped with resistive heaters capable of up to 250 W to simulate beam heating and thermometers to measure the temperatures.

The corrugated copper tube serves as the heat exchanger pipe and is inserted inside of an outer diameter of 168 mm stainless steel pipe. The corrugated pipe is separated from the outer shell pipe by four equally spaced spiders. Another stainless steel pipe with an outer diameter of 143 mm, serving as a dummy magnet pipe mounted with heater and thermometers, is placed below the heat exchanger. The two pipes are connected to each other at the end through an 89 mm outer diameter reducer and tee. The reason to choose the smaller size pipe at the heat exchanger end is because the space at the interface of the inner triplet interface is restricted. On the other hand, the reduced pipe size at the inner triplet interface will not cause significant increase of the temperature drop in that region. Table 3 lists all relevant parameters of the corrugated copper tube.

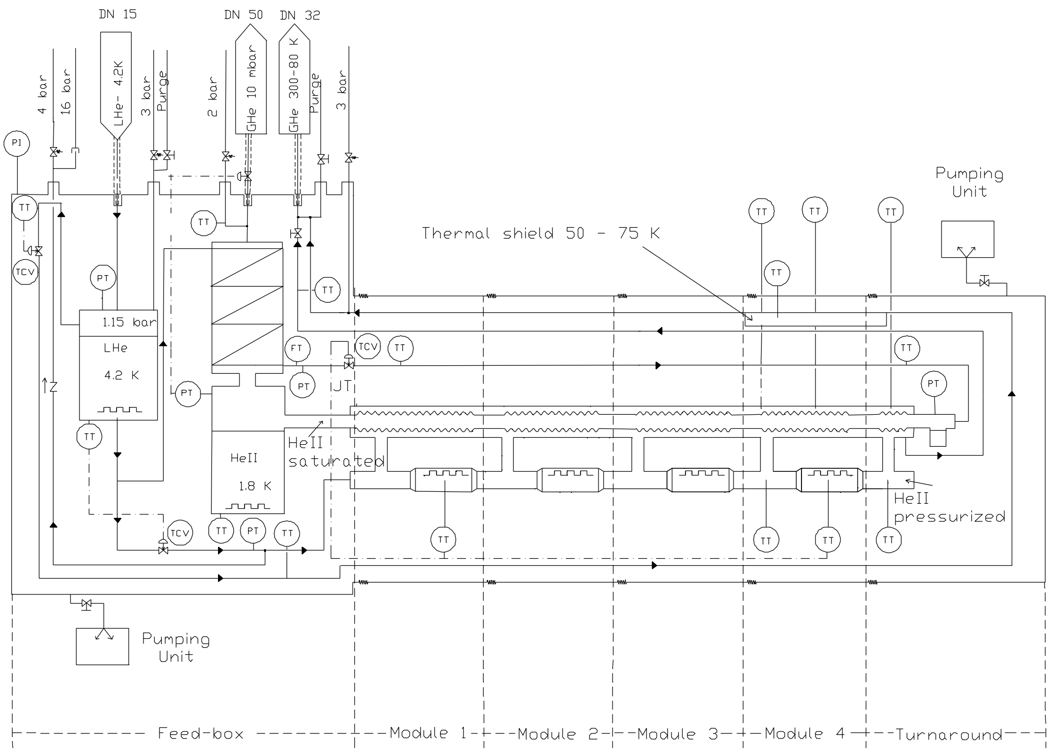

Figure 2. A simplified flow schematic of the He II heat exchanger test unit

Figure 3 shows the side view of one of the four modules. Besides the heat exchanger pipe and dummy magnet pipe mentioned above, two 38 mm tubes located on opposite sides are used to cool the thermal shield with cold helium vapor. A 19 mm stainless steel tube, which is connected to the outlet of the JT valve, is used to supply the saturated helium to the inside of the corrugated copper pipe at the turnaround end. During the system cool down from room temperature to liquid helium temperature, a 38 mm tube is welded to the shell-side of the heat exchanger outside of the corrugated pipe and serves as a cooldown return.

32 layers of MLI are used to reduce the thermal radiation from the room temperature to the thermal shield. Another 32 layers of MLI are wrapped on the 1.9 K test section to further reduce the heat leak from the thermal shield to the 1.9 K environment.

All thermometers and heaters are mounted in the pressurized helium side as marked in the flow schematic in Figure 2. The wires are routed out via a 6.3 mm OD tube to the room temperature. All joints are welded except the instrumentation pin connectors, where a rubber O-ring is used to seal at room temperature.

Table 3. The parameters of the corrugated tube

Corrugated tube material	Copper
Outer diameter (mm)	97
Wall thickness (mm)	0.7
Corrugation pitch (mm)	12.7
Corrugation depth (mm)	6.0

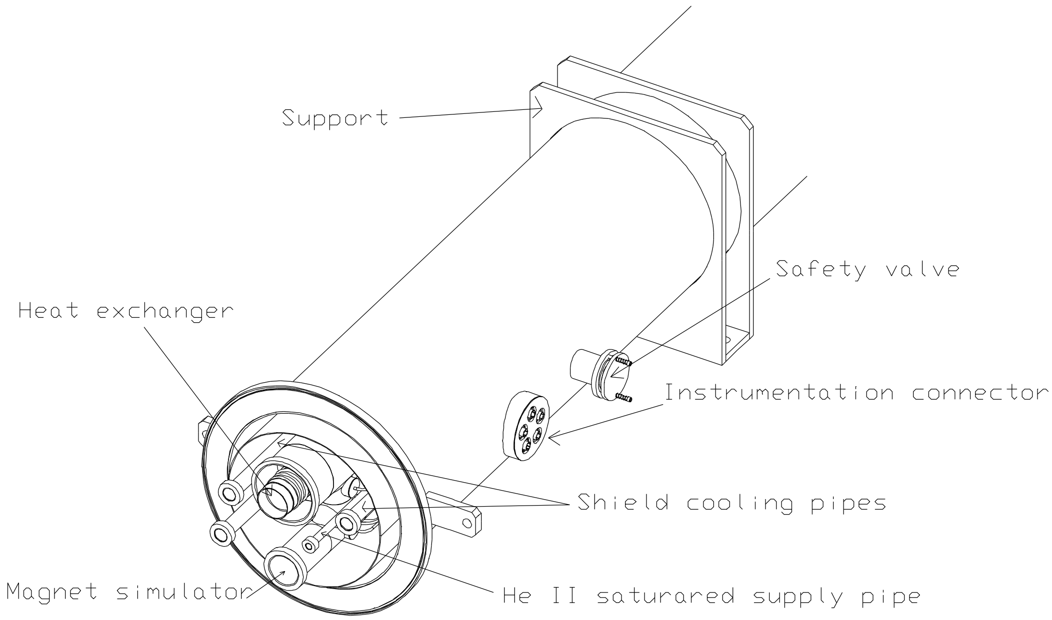

Figure 3. Side view of one of the four identical modules

FEEDBOX

The feedbox is between the CERN test stand and the heat exchanger test unit. The main function of the feedbox is to regulate and control the flow during different stages of the test run. The feedbox consists mainly of the valves, phase separator, counter flow heat exchanger (also called JT heat exchanger), liquid helium accumulator, instrumentation sensors, and safety valves. An overview of the feedbox without the thermal shield and vacuum vessel is shown in Figure 4.

All control valves and safety valves are mounted on the top flange. The interface connection between the CERN test stand and feedbox is located on the top flange as well. The other end of the feedbox is connected to one of the four identical modules, using the standard interconnect. The instrumentation connectors are located on the side of the feedbox. The instrumentation sensors include a turbine flow meter, heater, level indicator, pressure transducer and thermometer, all used to control and fine-tune the parameters of the system during the experiment. The flow meter is mounted just before the JT valve to measure the total flow rate of liquid helium into the heat exchanger. A heater is located in the helium accumulator to vaporize excess liquid helium to keep the counterflow heat exchanger from overflowing. Thermometers mounted inside the counterflow heat exchanger are used to monitor the thermal performance of the heat exchanger. The pressure sensor inside of the helium accumulator can be used to measure the saturated He II temperature and regulate it if necessary.

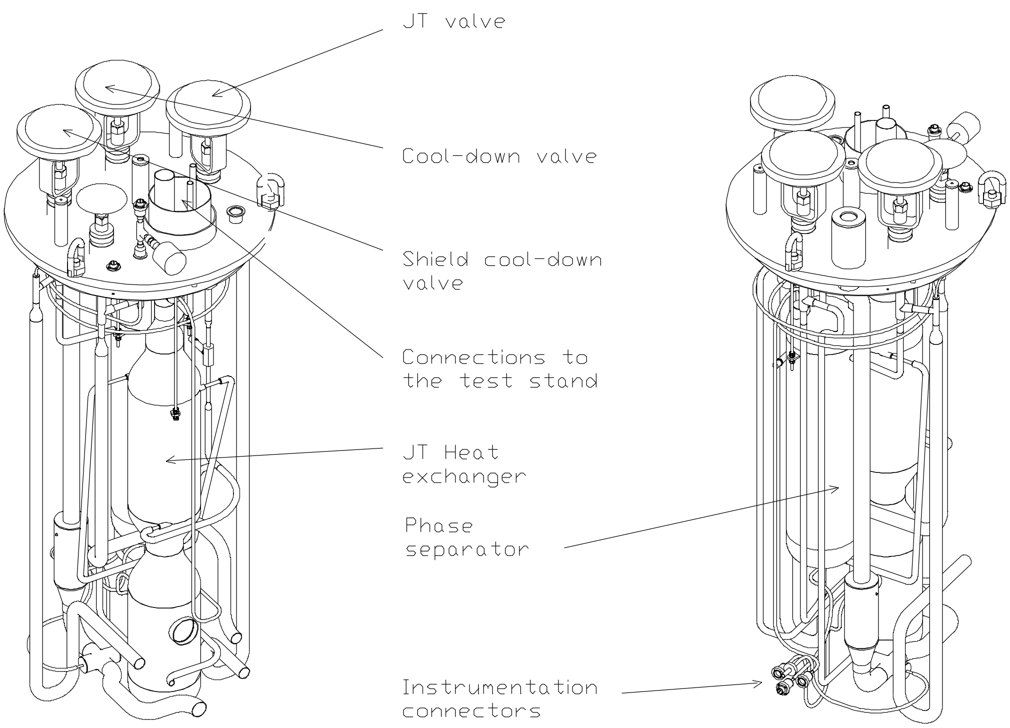

Figure 4. The feedbox without the thermal shield and vacuum vessel

The interface between the feedbox and the CERN test stand is simply three pipes approximately 3 meters above the ground. One pipe is to supply saturated helium at about 1.2 bar. The second pipe is the low-pressure return and used for the initial cooldown and thermal shield cooling return. The third pipe is connected to the cold compressor and serves as the very low-pressure return. The other parts of the test stand include the control valves and instrumentation sensors but are beyond the scope of this report.

SUMMARY

The full size He II heat exchanger test unit for verifying the LHC inner triplet cryogenic system has been designed. The four modules and turnaround end are complete. The feedbox is now in the manufacturing process and should be delivered to Fermilab in later October this year. The experimental data from the test unit will give us a verification of the LHC inner triplet cryostat design. The heat exchanger test unit is expected to remove a heat load up to 180 W from pressurized He II at 1.9 K with a temperature drop around 50 mK. The current schedule is to ship the heat exchanger test unit from Fermilab to CERN by the end of 1999; in order to foresee the measurement campaign by mid 2000.

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